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Development and Testing of the Tropospheric Trace Species Sensing FPI Prototype (TTSS-FPI)

Earth Science Technology Conference (ESTC)

June 28, 2006

University of Maryland University College

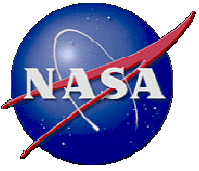
A. Larar, B. Cook, C. Mills, M. Flood, E. Burcher, & C. Boyer

NASA Langley Research Center

J. Puschell, Raytheon SBRS

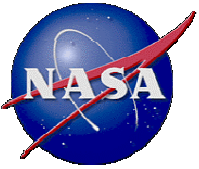
W. Skinner, UM-SPRL





Topics

- **Scientific Motivation**
- **Measurement/Instrument Concepts**
- **TTSS-FPI (IIP) Results**
 - Program overview
 - Progress-to-date
 - **Laboratory testing & data analysis**
- **Summary & Way-Forward**



Science Motivation

- **Tropospheric chemistry identified as key measurement area for future NASA Earth science missions (*NASA SMD Strategic Enterprise and Science Research Plans*)**
- **Tropospheric ozone (O_3) clearly recognized as one of the most important gas phase trace constituents in the troposphere**
 - **key oxidant in tropospheric photochemistry**; O_3 photolysis is one of the principal sources of the hydroxyl radical (OH), the most important radical species associated with the photochemical degradation of anthropogenic and biogenic hydrocarbons
 - **exposure to enhanced levels negatively impacts health, crops, and vegetation**; O_3 is responsible for acute and chronic health problems in humans and contributes toward destruction of plant and animal populations
 - **greenhouse gas**; contributes toward radiative forcing and climate change
 - **Levels have been increasing and will continue to do so as concentrations of precursor gases (oxides of nitrogen, methane, and other hydrocarbons) necessary for the photochemical formation of tropospheric O_3 continue to rise**; there is evidence suggesting that average surface O_3 concentrations may have doubled over the last century
- **Space-based detection of tropospheric ozone critical for enhancing scientific understanding & lessening impacts of exposure to elevated concentrations**
 - **spatially heterogeneous & high levels are not unique to urban areas**; non-uniform sources/sinks & transport; enhanced tropospheric O_3 observed over the south tropical Atlantic Ocean

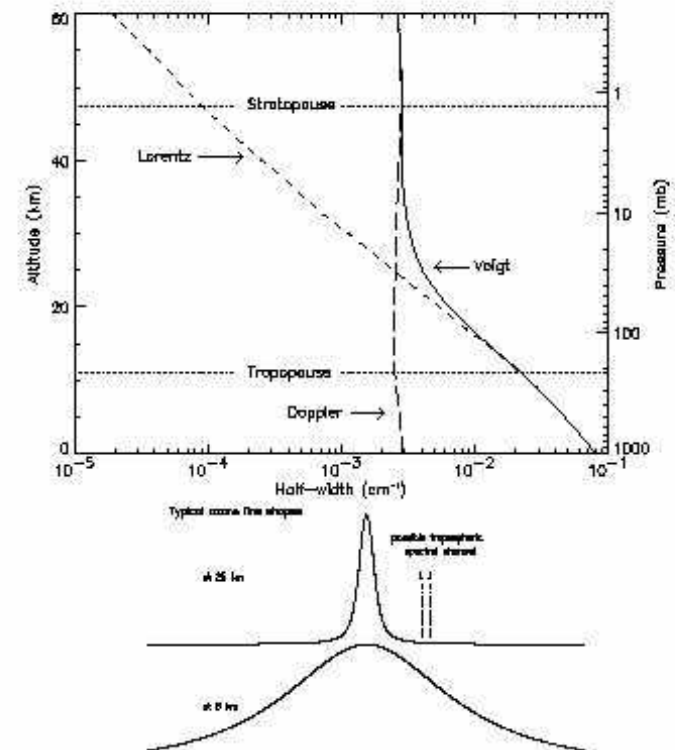


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Measurement & Instrument Concepts

- **Measurement Concept:** Spectrally isolate pressure-broadened wings of strong 9.6 micron ozone lines to enable tropospheric ozone mapping from a geostationary-based platform
 - continuous day/night coverage independent of solar zenith angle
- **Instrument Concept:** Spatially imaging double-etalon FPI system
 - LRE, HRE, & ultra-narrow filter in series configuration
 - spatial imaging with advanced FPA
 - active control loop for spectral tuning and parallelism control



FPI

(high throughput & spectral resolution)

+

Double-etalon configuration

(single-order transfer fn)

+

GEO-based imaging system

(high space & time resolution; maximize SNR)



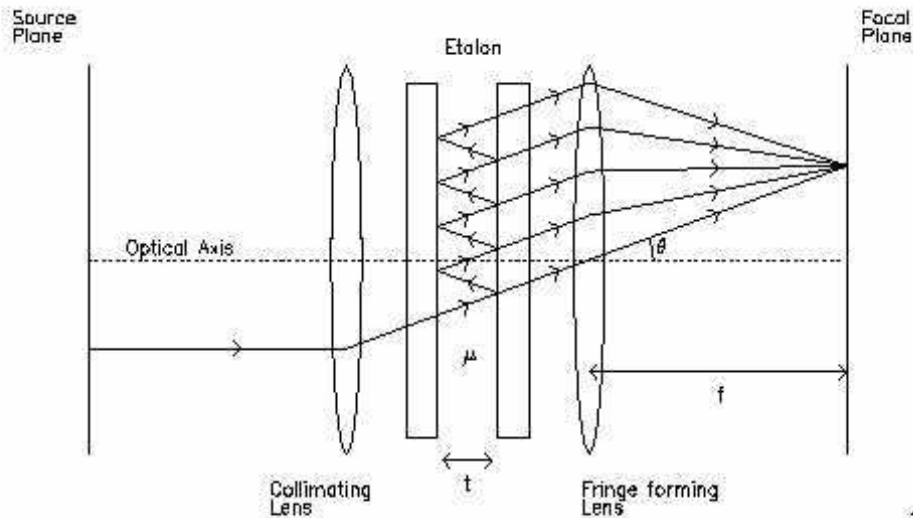
Spectral isolation capability; minimize undesirable signal contributions (interferant species, surface, & clouds)



Etalon Characteristics

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Monochromatic Ray Propagation Through Simple FPI



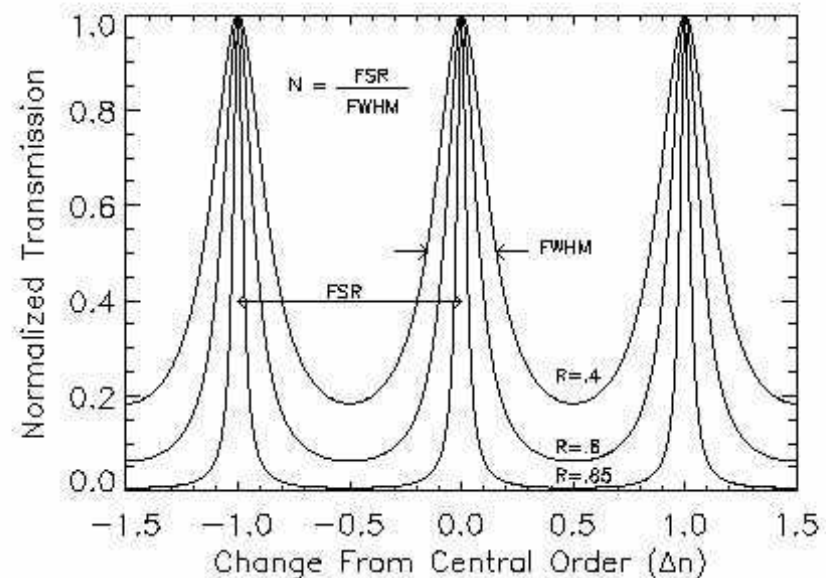
• *Constructive interference produces transmission maxima at resonant wavelengths, yielding periodic transmission function*

• *Additional etalons can be added in series to eliminate unwanted passbands, improve sideband rejection, and extend the effective FSR*

• *Acquire spectral information by tuning spectroscopic variables: mechanical (t), pressure (μ), and spatial (or angular, θ) scanning*

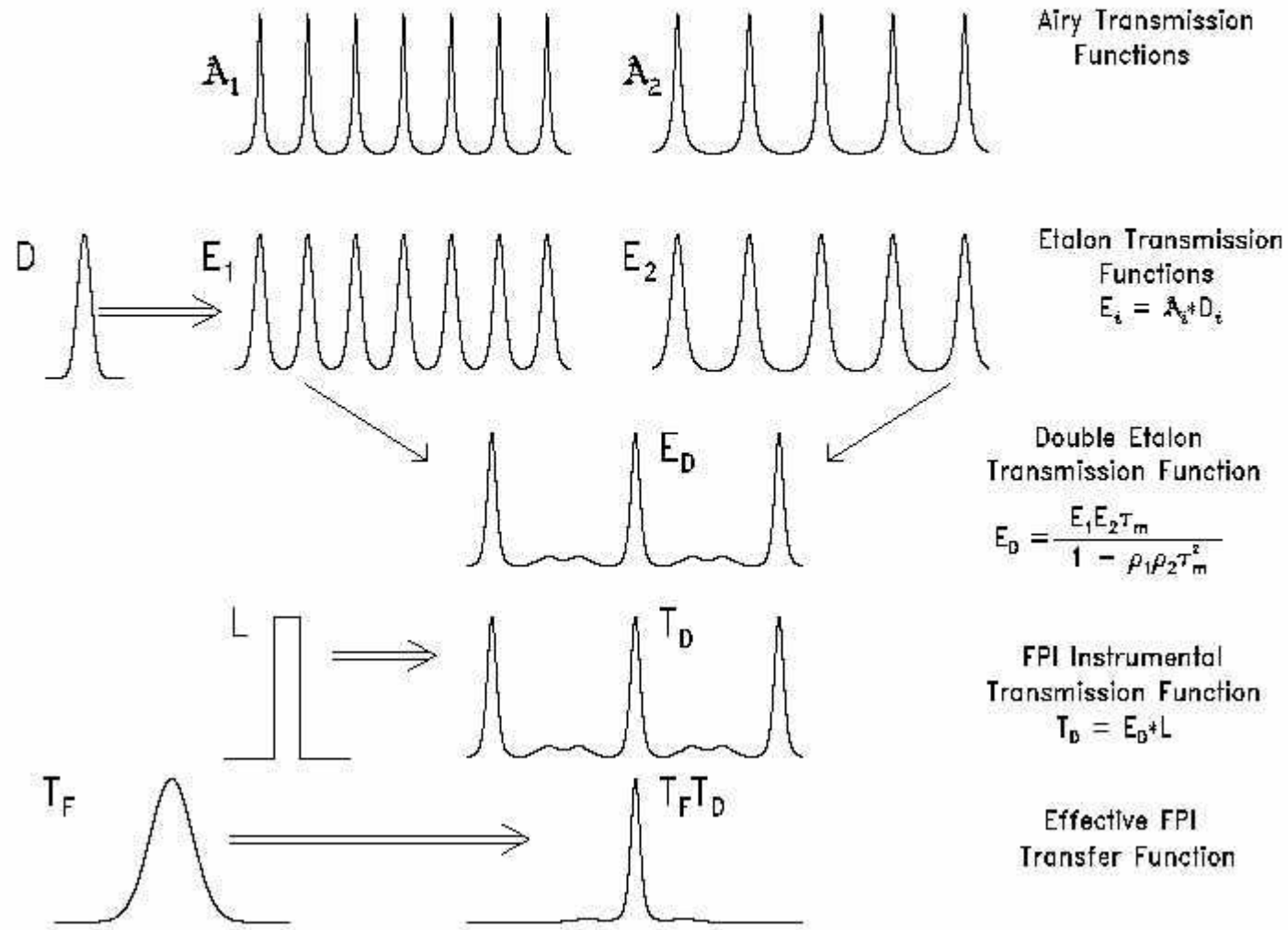
• *Spectral & spatial variability across focal plane for imaging configuration*

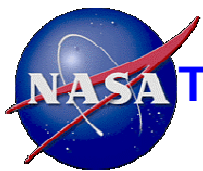
Airy function (ideal etalon) transmission





Formation of Single-Order Double-Etalon Transfer Function





Instrument Incubator Program - IIP

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Tropospheric Trace Species Sensing Fabry-Perot Interferometer (TTSS-FPI)

PI: Allen Larar / NASA Langley

Description and Objectives

Advance key technologies and demonstrate an integrated system for enabling cost effective remote sensing of the troposphere

Instrument uses a spectrally tunable imaging FPI to provide high spectral resolution over narrow spectral range

Space implementation focus on measurement of tropospheric ozone from Geo; Geo provides high temporal/spatial measurement capability

Approach

Develop airborne instrument prototype
Perform testing, characterization, and demonstration [ground-based radiometric, spatial, spectral within IIP]

- Validate measurement concept/technologies
- Demonstrate autonomous operation

Process and analyze engineering and science data
Define instrument concept for space-based sensor

Partners

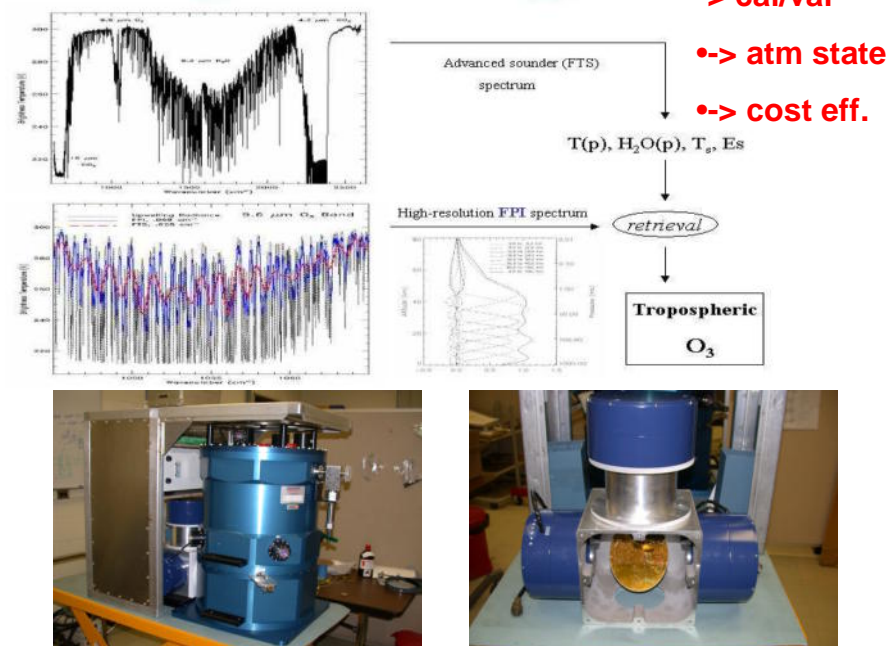
CoIs:

Dr. William Cook, LaRC

Dr. Jeffery Puschell, Raytheon SBRS

Dr. Wilbert Skinner, U of Michigan

Integrated Sensor Approach

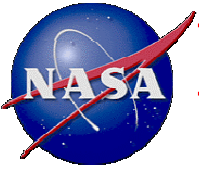


Schedule

Program start – Mar 02
Complete instrument assembly – Jan 06
Complete lab characterization and testing – 15 Mar 06
Complete space sensor concept study – Mar 06
Complete Final Report – Apr 06
Pursue ground-based & flight demo opportunities – FY06+

Applications/Mission

Future science objectives include O₃, CO, CO₂, N₂O and other tropospheric trace species; environmental monitoring, atmospheric chemistry, validation (GOES, ESSP, NPOESS)



Enabling Technologies Required for Measurement Concept

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- › Three technologies are required for TTSS-FPI within IIP to enable the **spectrally tunable imaging FPI** measurement technique for achieving high-resolution over narrow spectral ranges:

1) precision control of etalon plates

- a) to demonstrate accurate spectral tuning and parallelism control of the LRE and HRE; including piezo-electric actuators in a capacitance-based feedback system

2) high-sensitivity two-dimensional infrared detector array

- a) to demonstrate spatial imaging and required SNR; desire advanced materials for higher-sensitivity operation at warmer temperatures, with goal of reducing active cooling requirements, for space-based applications

3) spectral and radiometric calibration

- a) to demonstrate spectral registration and absolute intensity fidelity in radiance measurements; requires stable & narrow spectral emission character sources

Approach

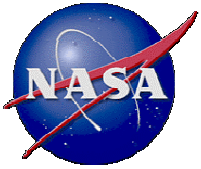
Demonstration

1) & 3): quality spectra (independent spectral elements of proper resolution, SRF, and magnitude).

2): spatial imaging

Verification

simulation & inter-comparison with other obs.



Instrument/System Initial Specifications

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Instrument Parameter^a

Airborne System^b

Etalons

Diameter	~ 8 cm (6 cm active area)
Free Spectral Range (HRE, LRE)	1.52 cm ⁻¹ , 5.46 cm ⁻¹
Scan Range (LRE/HRE)	~ 5 / 15 micron

NB filter

Transmission characteristics	3 – 5 cm ⁻¹ FWHM; $\tau > 50\%$; ~ Gaussian shape; 7 – 12 cm ⁻¹ FW 5%
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FPA

Format	160x160 (~40x40, effective)
Pixel Size	60 μm x 60 μm (~240 x 240 eff.)
Operating Temperature	35 – 65 K (~40K, nominal)
Effective D*	~ 3.0 E ¹² cm Hz ^{1/2} /W

Overall System

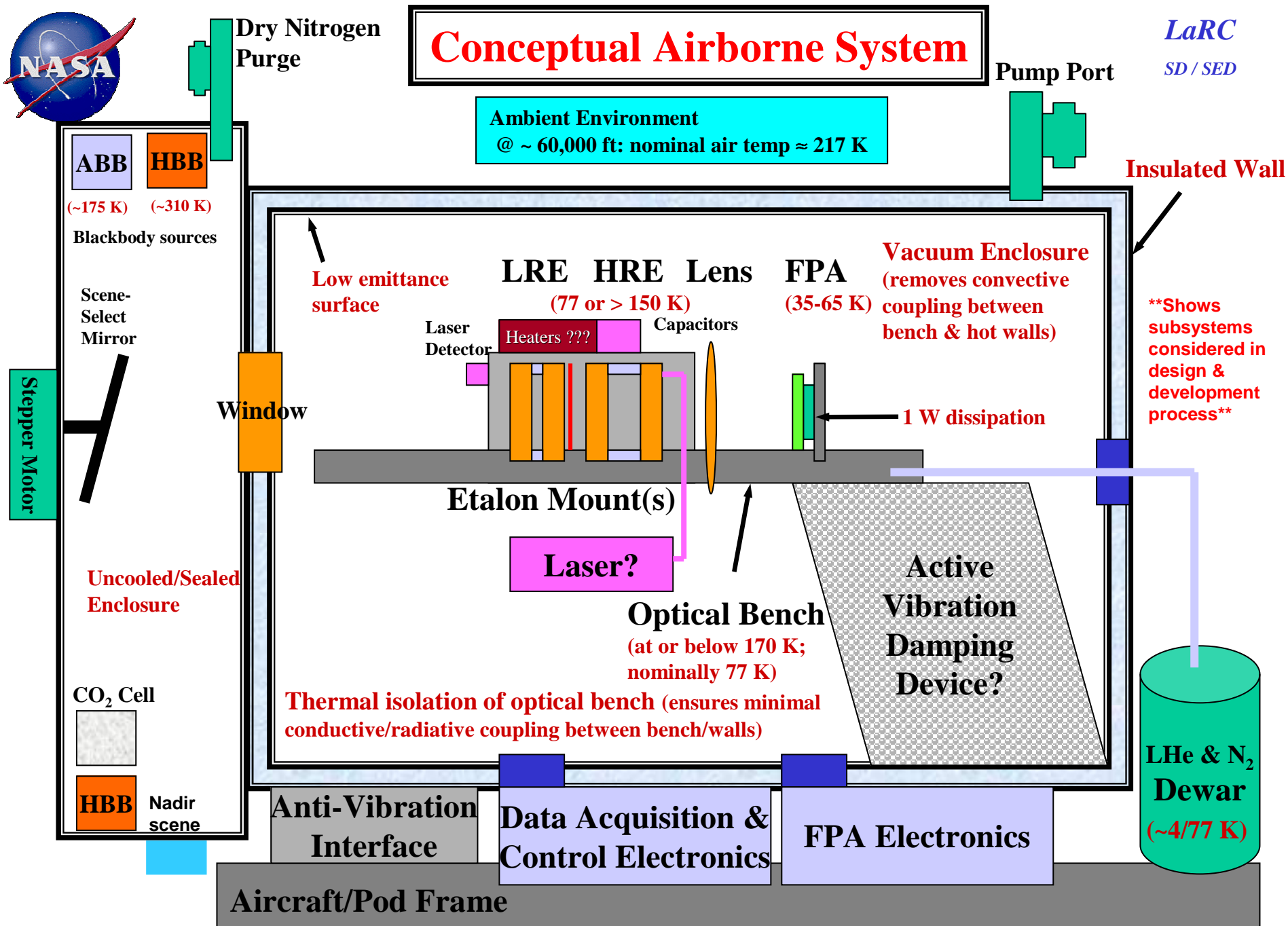
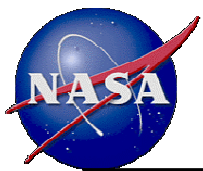
Optical System Peak Transmittance	~0.35
Effective System Finesse	~ 20
Spectral Resolution	0.068 cm ⁻¹
Spectral Range	~ 1053.5 – 1056. cm ⁻¹
f/#	~ 3.0
Spatial Resolution ^c	~6.3/8.1 m (~25/32 m, eff.), ~1.0/1.3 km across FPA
Dwell Time per Spectral element	~0.26 s
Dwell Time per Spatial Sample	16 s for spectrum (~ 60 elements)
Coverage Time	1.76 km along a/c track in 16 s
Platform altitude	~ 16 km
Data rate/storage ^d	~ 2-20 MB/s / 60 GB (8hrs)
Instrument size (dewar + rack)	~35”h, 22”w, 42”d

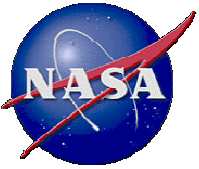
^a assumes NESR ~ 0.15 mW m⁻² sr⁻¹ cm

^b nominal parameters desired; actual ones are fcn of obtainable FPA characteristics (i.e., D*, format, pixel size)

^c assumes 3.7 degree IFOV for full FPA at Proteus (15.5 km)/ER-2 (20 km) altitudes

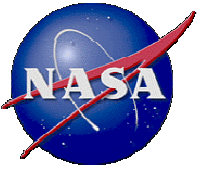
^d worst case range; nominal values TBD per frame averaging; further reduction from pixel binning





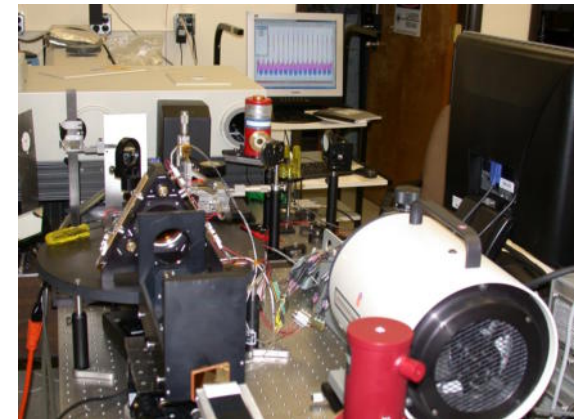
Technical Status Overview

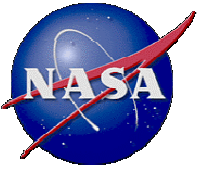
- Subsystem- and psuedo-system-level (i.e. w/ HRE in dewar) testing has demonstrated several project enabling technologies
 - Etalon control & spectral fidelity at room/cryo temperatures
 - Encouraging radiometric calibration w/FPA $\leq 77\text{K}$
 - Imaging fidelity @ nominal system cryogenic temperatures
 - Imaging FPI in dewar cryogenic environment
- Accomplished system-level testing in dewar prior to closure of IIP task (15 March 2006)
 - ILS characterization using CO_2 laser with HRE in dewar etalon assembly
 - w/o optimum cryogenic alignment / FPA illumination
- Initial alignment & FPA illumination issues have been resolved
 - cryogenically-induced alignment displacements are removed with new optical adjustment motors providing sufficient torque in dewar
 - Integrating sphere or beam diverging pre-optics provide extended source input



Lab Testing Approach

- **Parallel lab testbed mitigates risk and ensures continued technical advancement**
 - It's a slow, difficult process doing many of these tasks for the first time in a cryogenic environment
 - Bench level characterization testing continues, in parallel to dewar operations, with an independent measurement system (high-resolution laboratory FTIR, along with laser, BB, and solar sources)
- **Targeting data from both systems ensures continued technical advancement**
 - **Dewar:** ILS characterization across SCA, and to characterize etalon tuning & control in cryogenic environment
 - **Bench:** ambient characterization of etalon SRF, etalon tuning & control (HRE, LRE, & both in series)



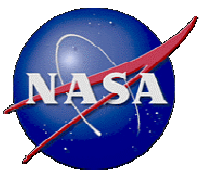


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Select Key Test Results...



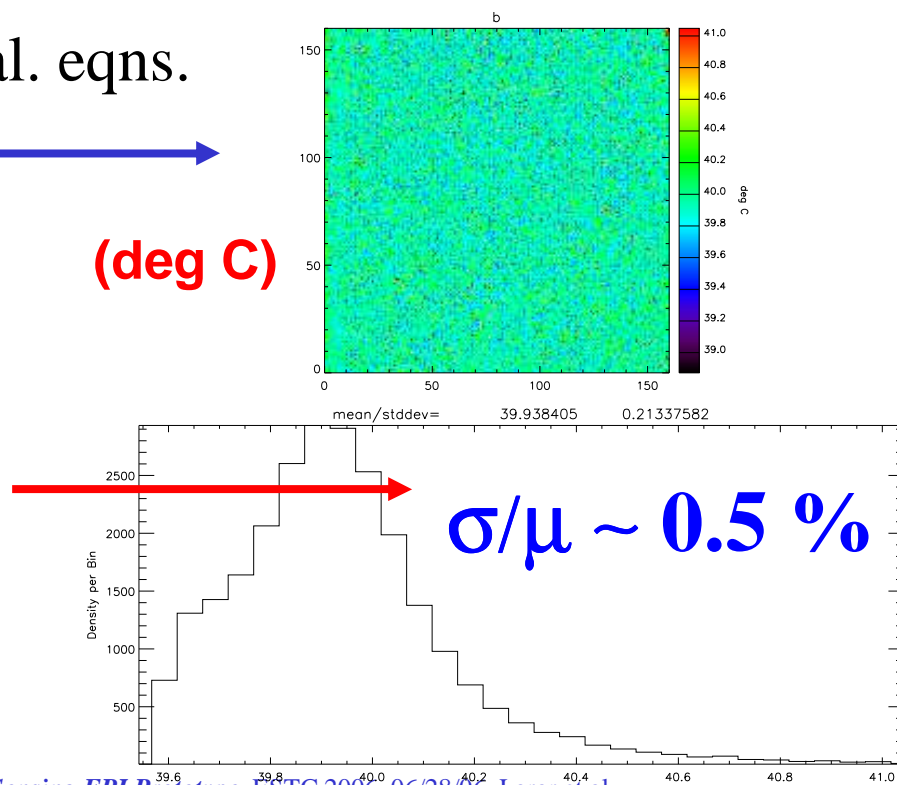
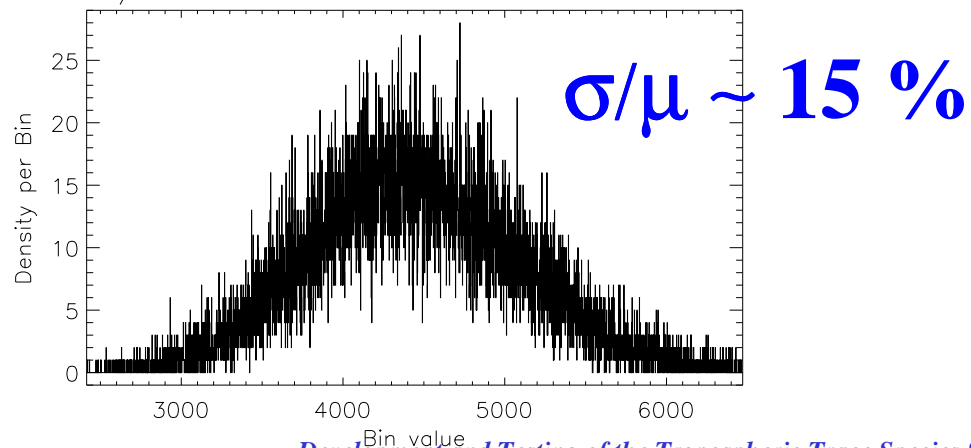
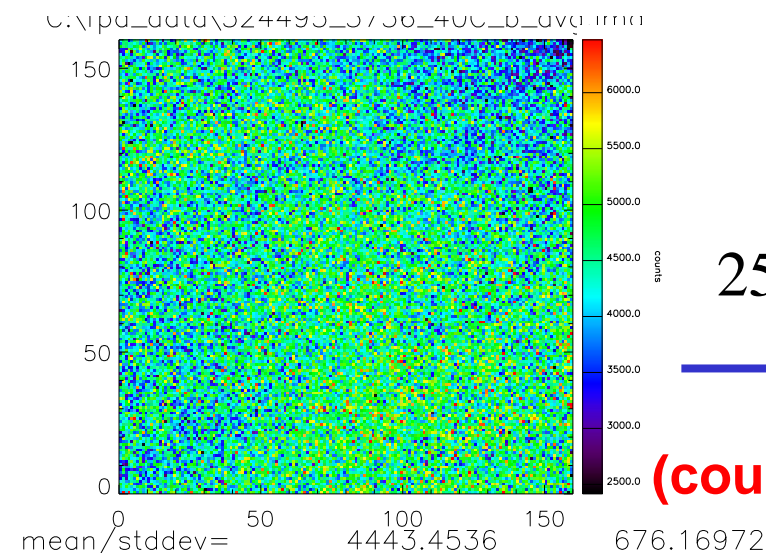
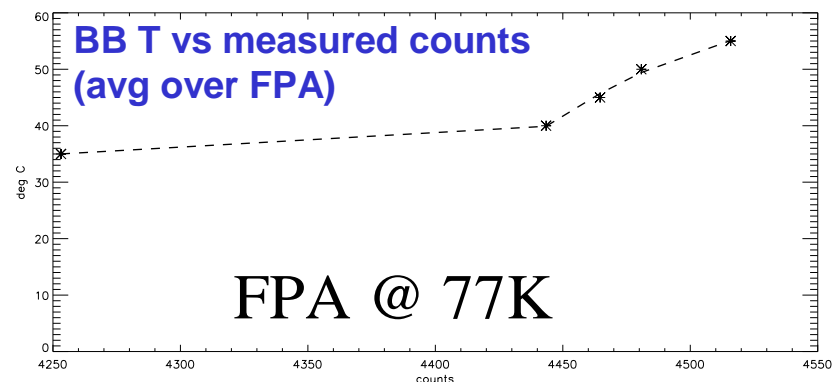
Development and Testing of the Tropospheric Trace Species Sensing FPI Prototype, ESTC 2006, 06/28/06, Larar et al.

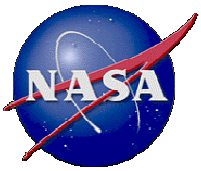


Radiometric Calibration Testing (Mar 2005)

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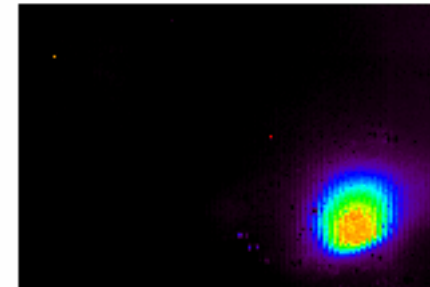
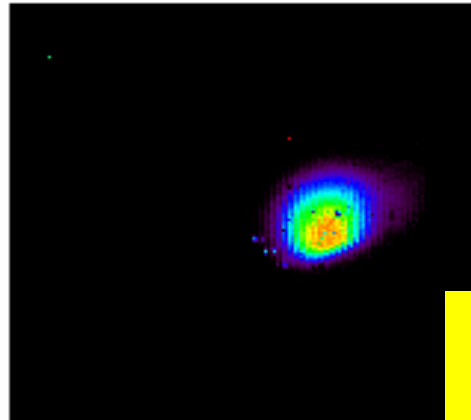
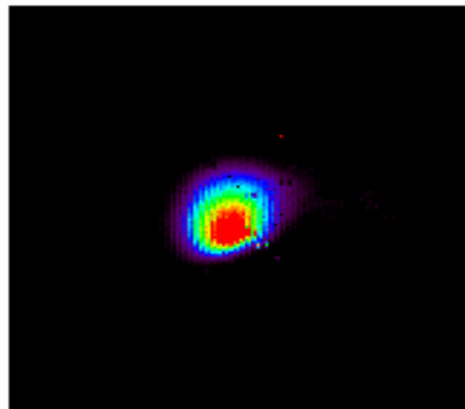
- Derived calibration equations for each pixel
 - LSQ fit to BB temperature vs measured counts relationships for each of the 25,600 pixels
- Applied calibration equations to measurements of 40 C BB





Elliptical Gaussian Modeling of Sun-look Imaging Test Data (091405)

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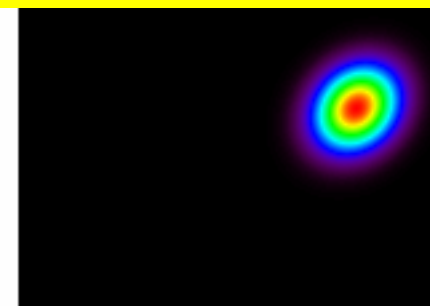
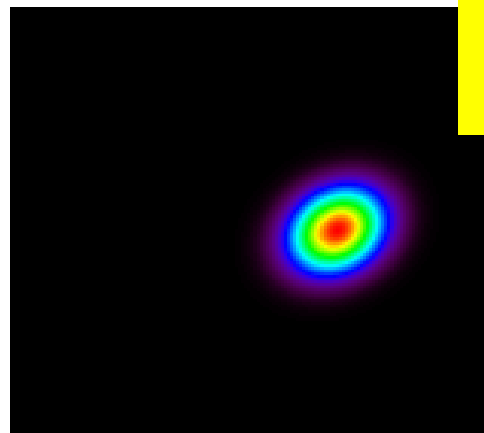
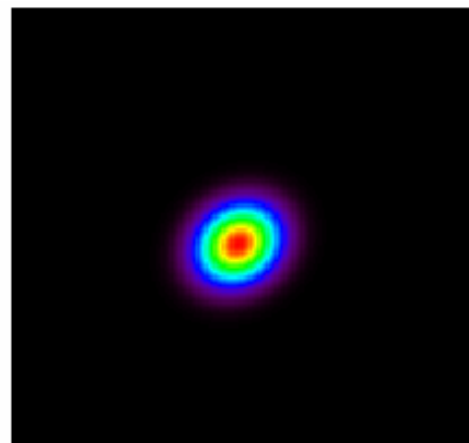


measured

"truth" = 23.48 pixels

Mean all obs= 23.18 (-1.3%)

**Mean of "good" tests= 23.475 (-0.02%);
stdev = +/- 0.41%**

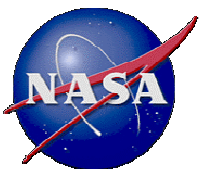


Simulated
(@ min RSS)

**Centroid = (77,74)
FWHM = (21.2,21.3)
Rot (CW, deg) = -14.4**

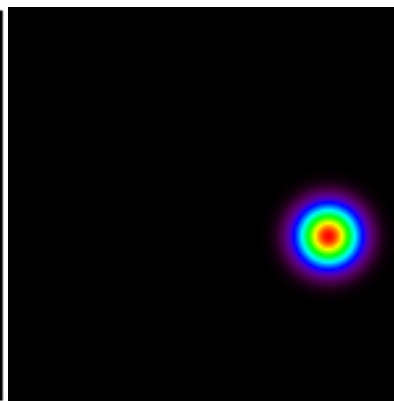
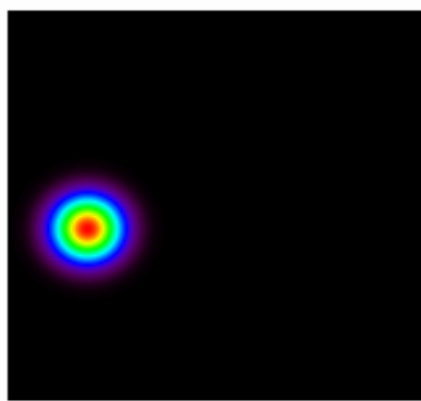
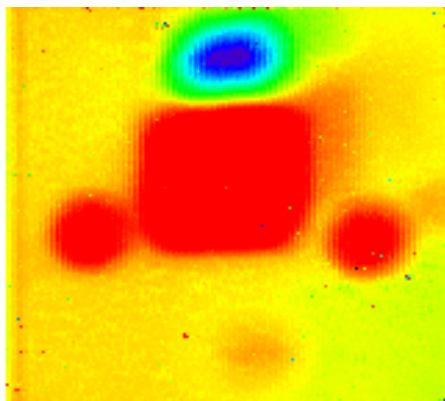
**Centroid = (107,76)
FWHM = (23.4,23.4)
Rot (CW, deg) = -18.0**

**Centroid = (126,76)
FWHM = (23.5,23.6)
Rot (CW, deg) = -18.0**

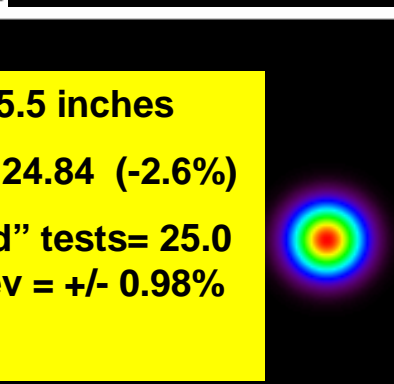
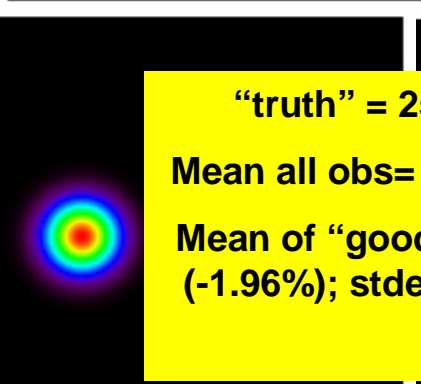
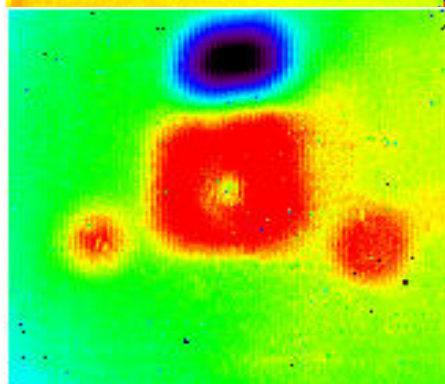


Hallway Imaging Tests (082605)

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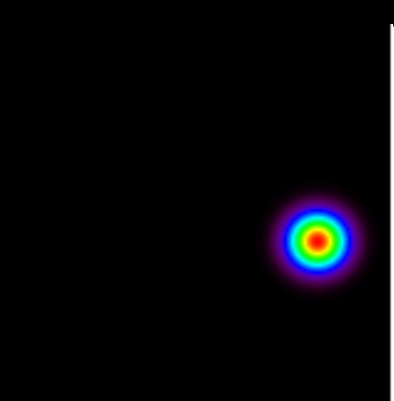
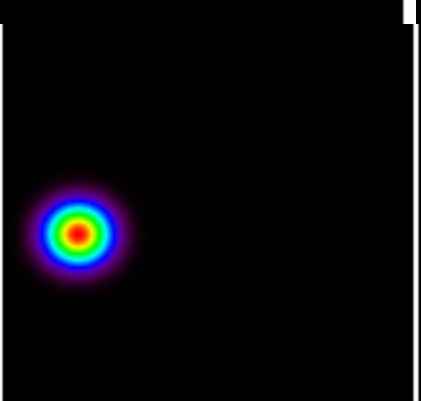
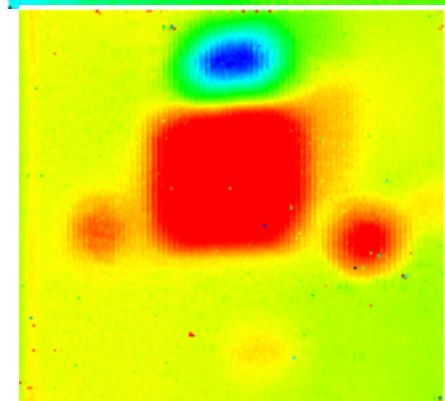


C:\fpa_data\test2\hallway\ice2_avg.img
Left BB: pos (c,r), dia-fwhm (pix), dia-fwhm (inches) =
30 70 20.8000 5.20000
Right BB: pos (c,r), dia-fwhm (pix), dia-fwhm (inches) =
130 68 18.2000 4.55000
BB horizontal distance (pixels / inches) =
100 / 25.0000
BB center-to-center distance (pixels / inches) =
100.020 / 25.0050

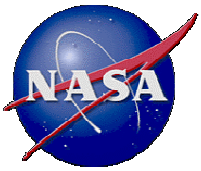


“truth” = 25.5 inches
Mean all obs= 24.84 (-2.6%)
Mean of “good” tests= 25.0
(-1.96%); stdev = +/- 0.98%

C:\fpa_data\test2\hallway\ice_R_avg.img
Left BB: pos (c,r), dia-fwhm (pix), dia-fwhm (inches) =
33 70 22.5000 5.62500
Right BB: pos (c,r), dia-fwhm (pix), dia-fwhm (inches) =
132 69 22.5000 5.62500
BB horizontal distance (pixels / inches) =
99 / 24.7500
BB center-to-center distance (pixels / inches) =
99.0051 / 24.7513

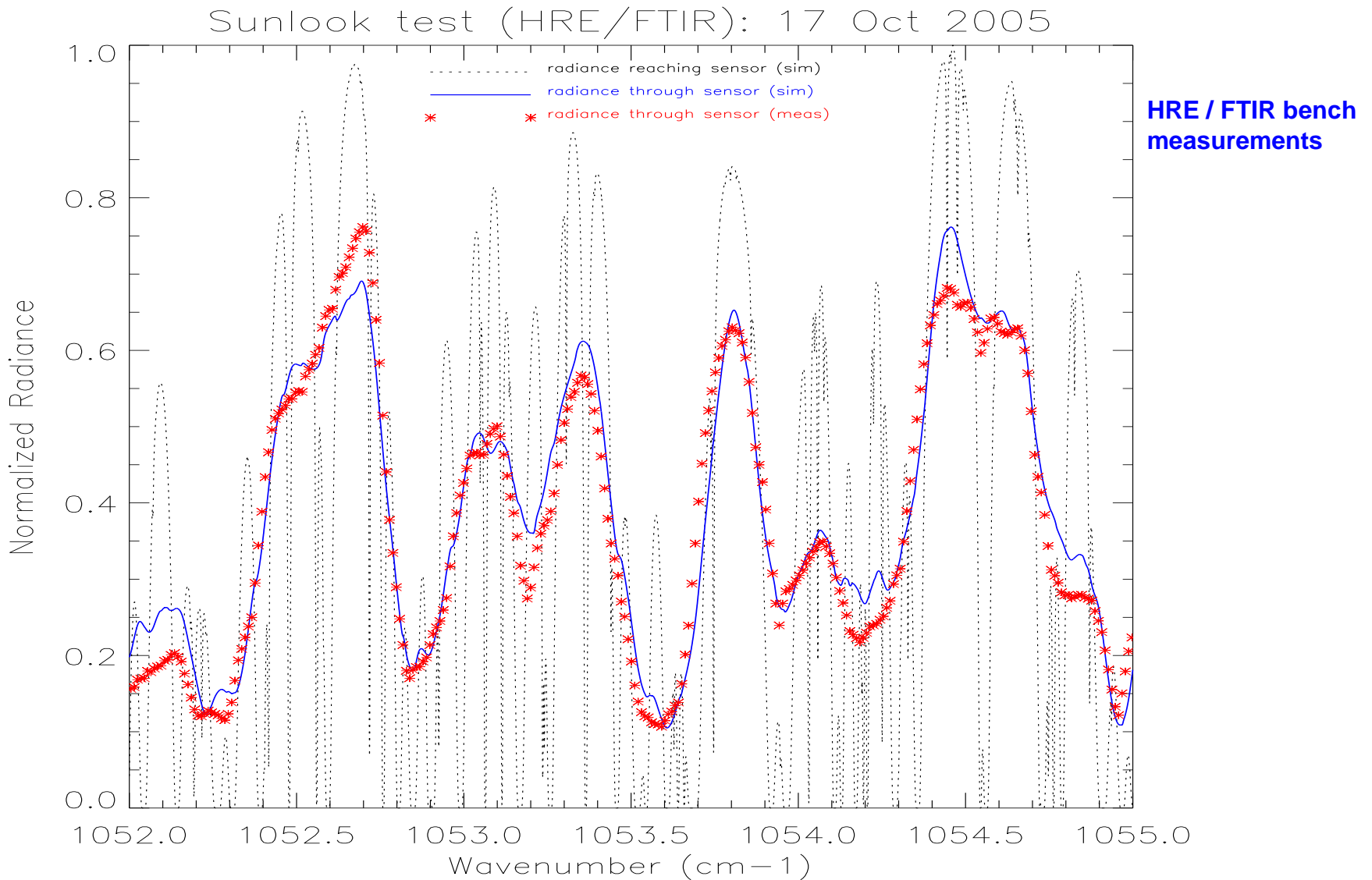


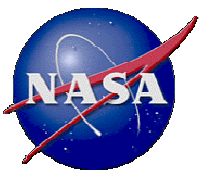
C:\fpa_data\test2\hallway\RonBB_avg.img
Left BB: pos (c,r), dia-fwhm (pix), dia-fwhm (inches) =
29 71 19.7000 4.92500
Right BB: pos (c,r), dia-fwhm (pix), dia-fwhm (inches) =
130 68 18.2000 4.55000
BB horizontal distance (pixels / inches) =
101 / 25.2500
BB center-to-center distance (pixels / inches) =
101.045 / 25.2611



Solar Spectra (17 Oct 2005)

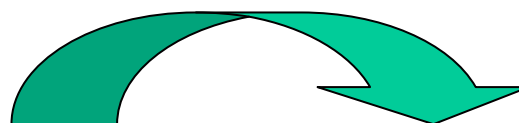
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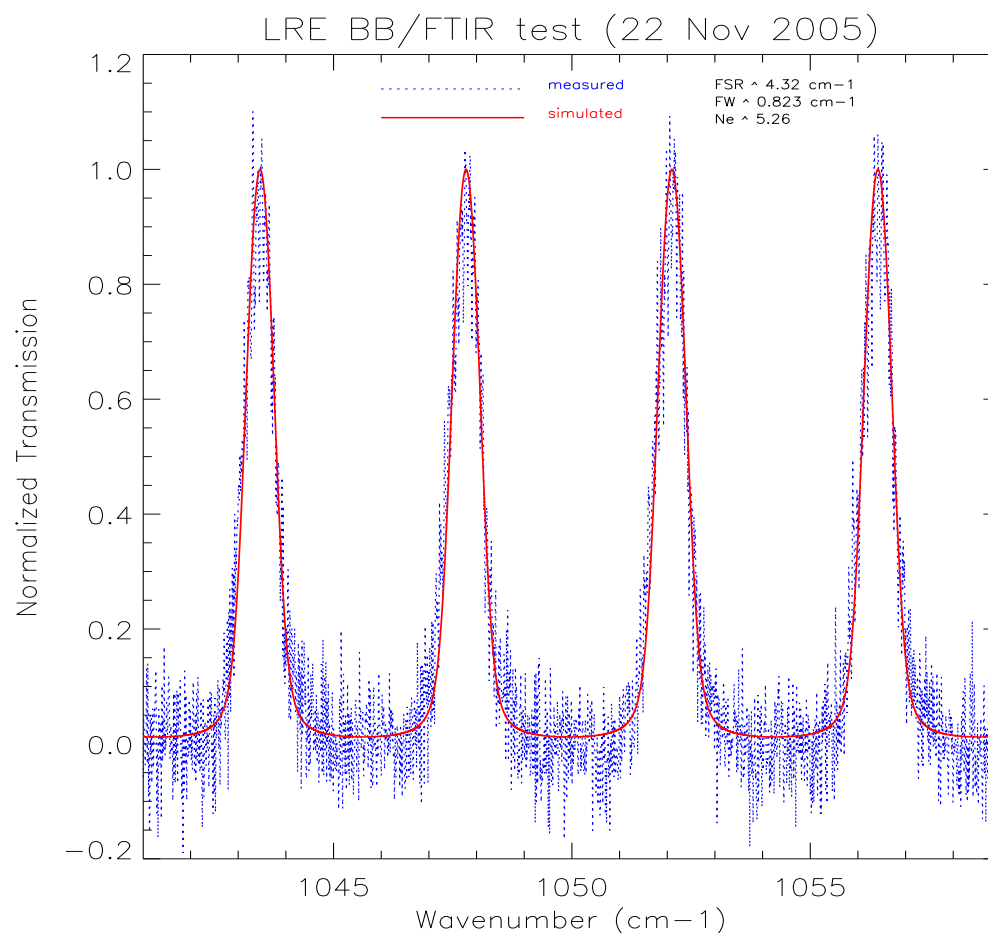
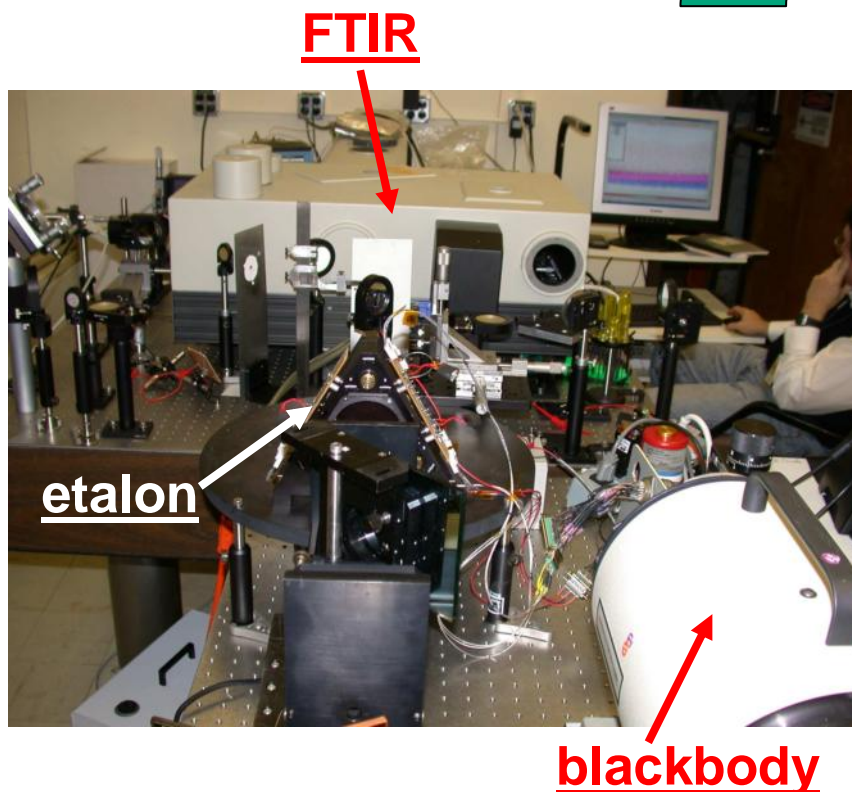


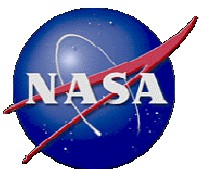
Etalon characterization testing with BB/FTIR: LRE example

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Post-test analysis infers
etalon properties to best fit
measured test data





Capacitance Repeatability Test (03/3-6/06)

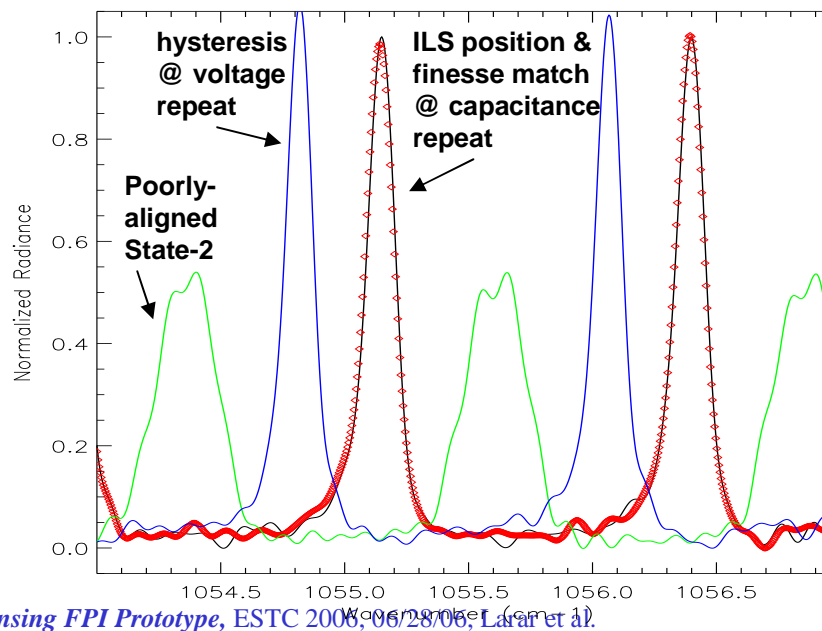
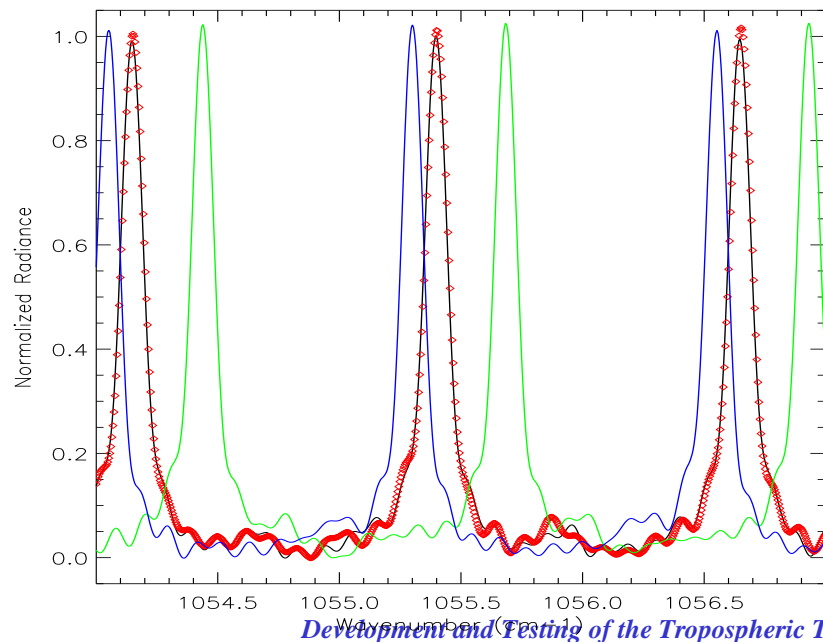
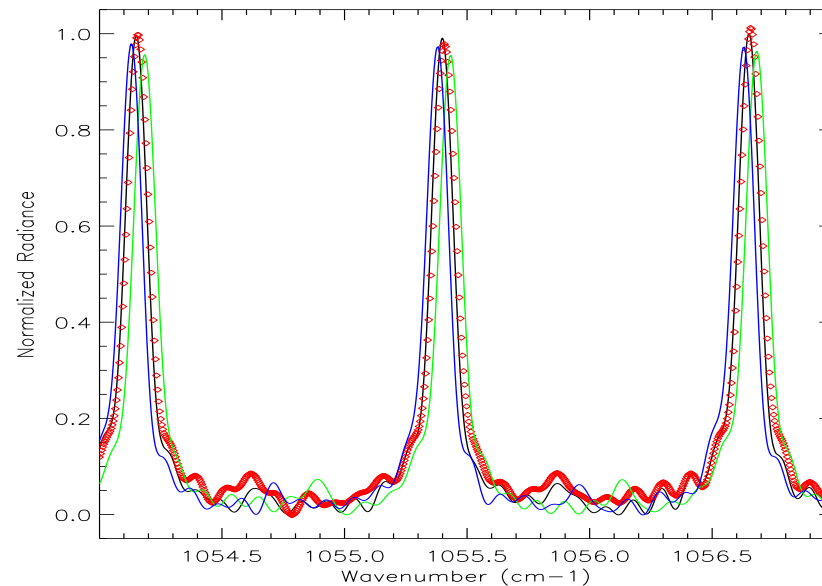
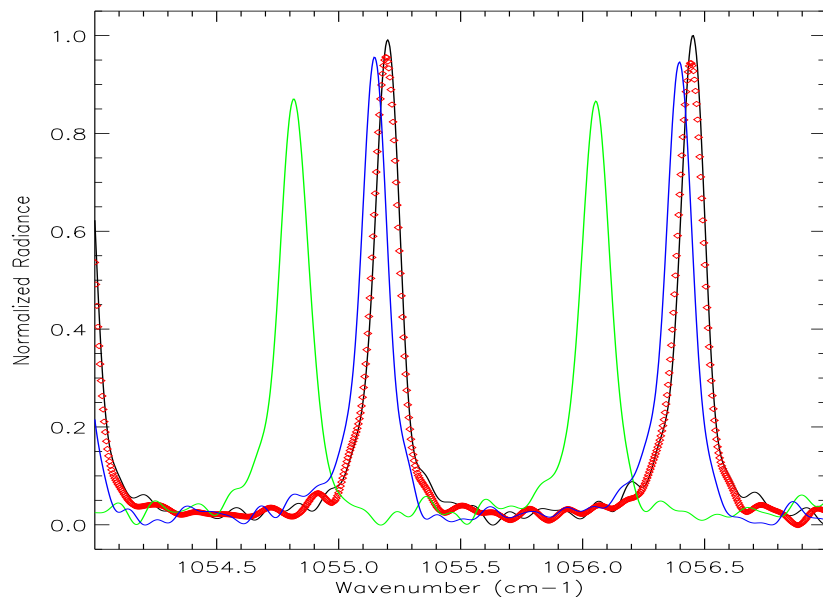
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State-1: —

State-2: —

Repeat-1 (voltage): —

Repeat-2 (capacitance):



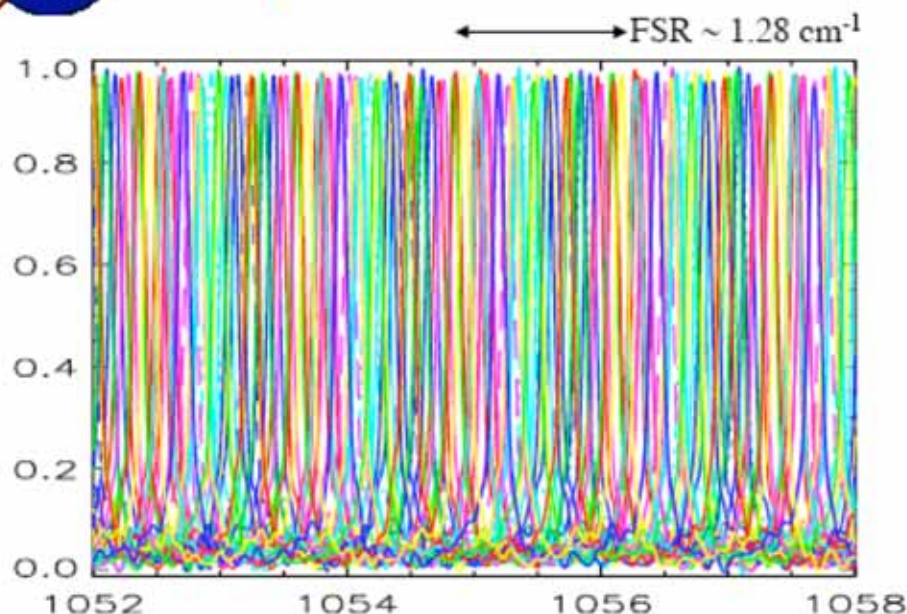
Development and Testing of the Tropospheric Trace Species Sensing FPI Prototype, ESTC 2006, 06/28/06, LaRar et al.



Capacitance Scan Test (030706)

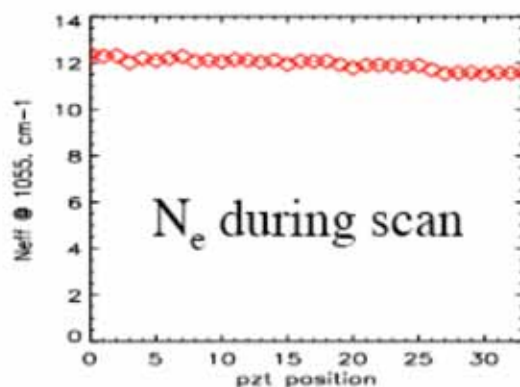
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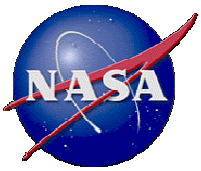
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HRE
passbands

Since repeatable with
capacitance (spectral
position & finesse), such
data will be used to derive
wavenumber vs
capacitance relationships
for “spectral calibration”





Movie of PZT scan of CO₂ laser source (031506)

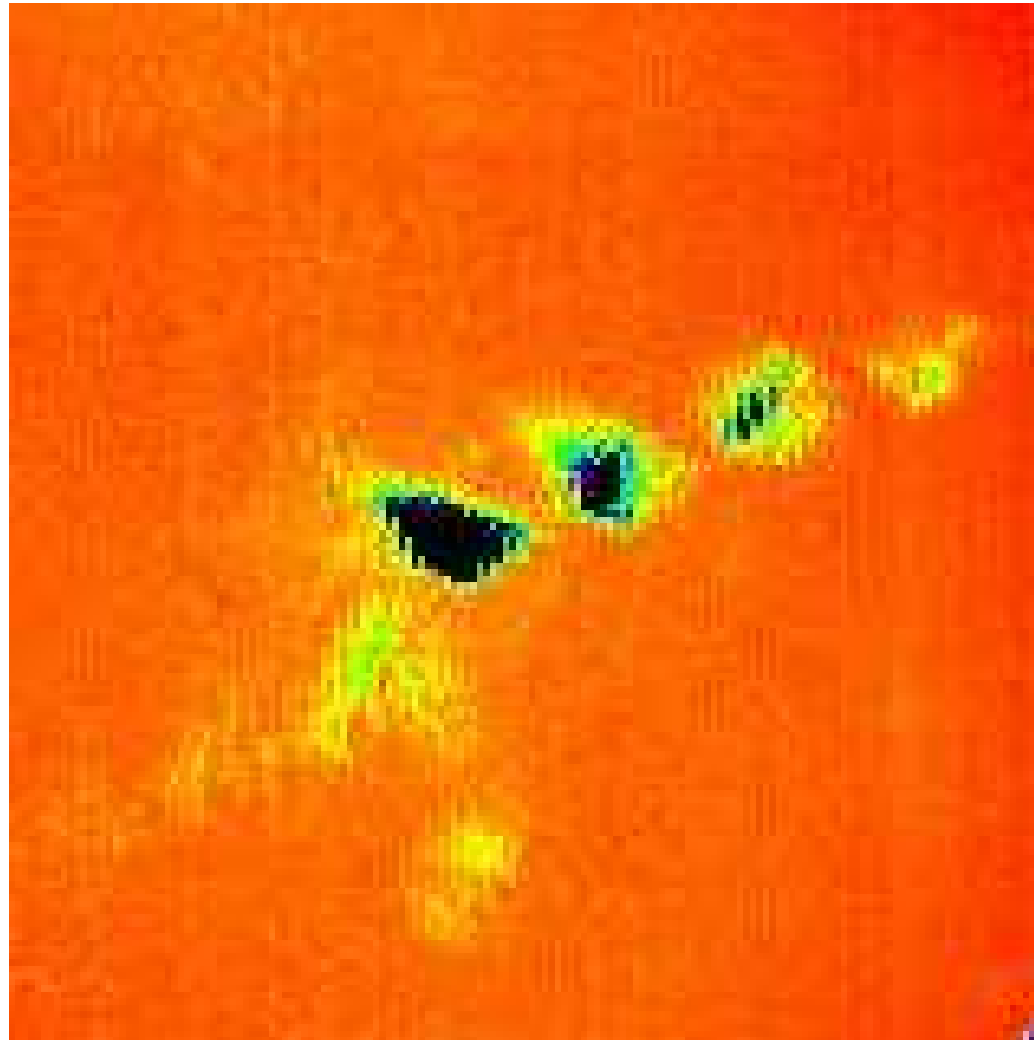
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Spectral
fringes
visible in
time-
varying
signal
portion of
illuminated
pixels!

Deviation from centered,
full-circular ring pattern
caused from:

Partially-illuminated FPA
↳ observation of only
portion of fringe

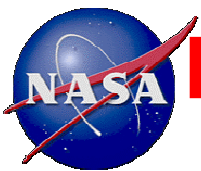
Mis-aligned etalon plates
& parasitic energy
reflections ↳ deviation
from circular & offsets



Original data (max
signal = min counts)

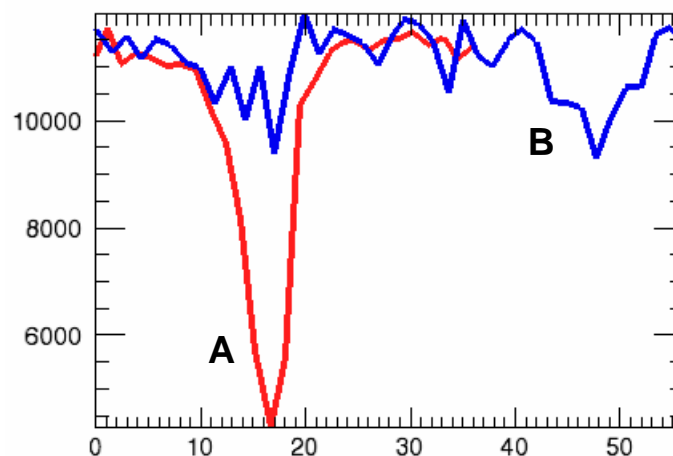
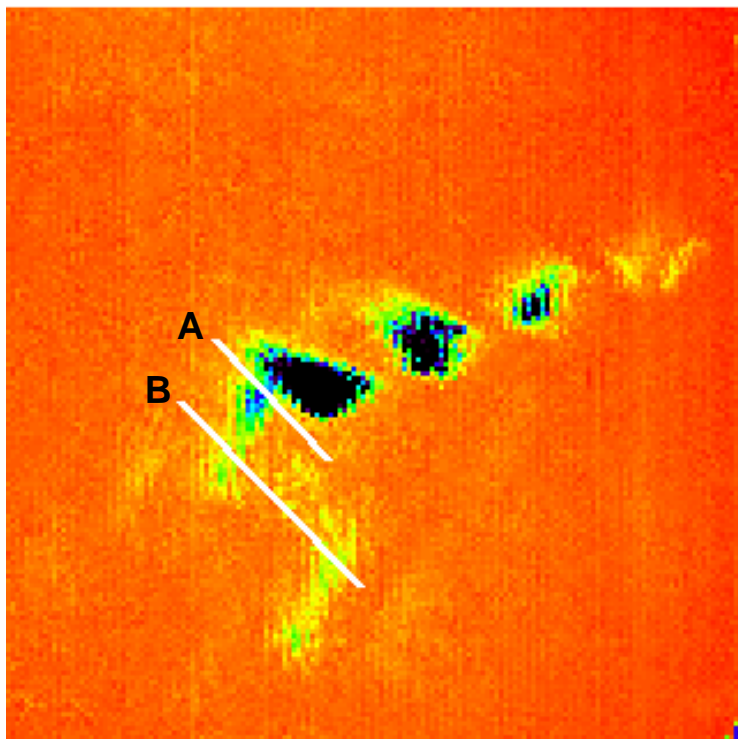
Intense laser signal
transmitted through
FPI bandpass wings,
saturating local pixels

Non-AR-coated dewar
window ↳ ghost
images



Effective Finesse Approximation from Cryogenic PZT Scan Test (031506)

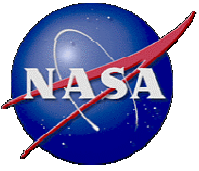
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$$N_e = \text{FSR} / \text{FWHM} \sim (47.56 - 13.64) / (18.68 - 13.48) = \boxed{6.52 \sim N_e}$$

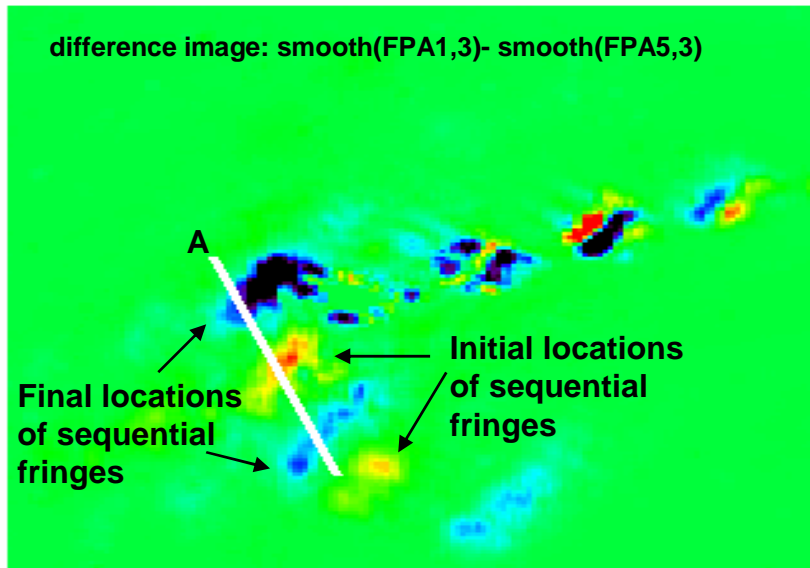
Ambient lab values have ranged from ~
6-14, as fcn of etalon alignment

**Dewar-derived value very representative of expected
etalon finesse after cryogenically-induced misalignment**

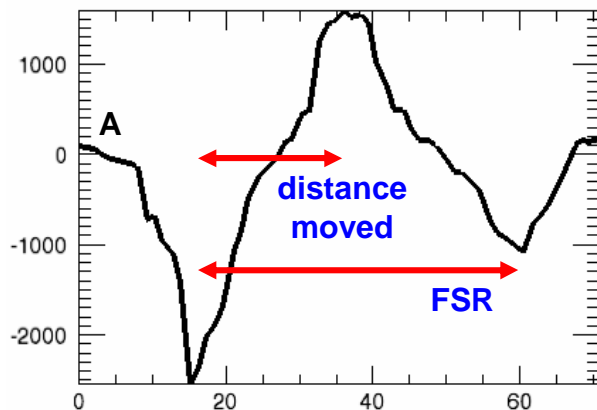
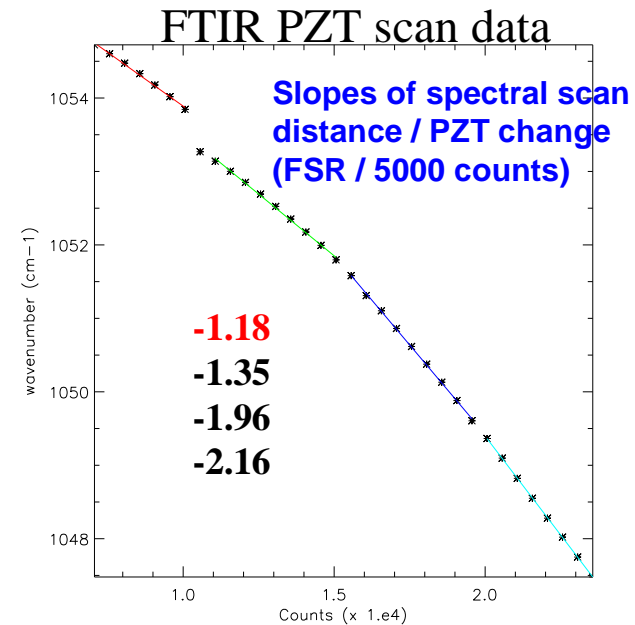


PZT cryogenic scan distance estimation (031506)

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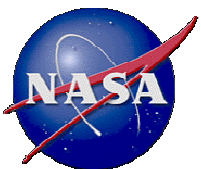
Distance moved / FSR $\sim (36.92 - 15.11) / (58.92 - 15.11) =$
0.497832



$\sim 1/2$ PZT range expected at cryogenic operation vs lab for same ΔV

5000 counts in lab ~ 1 FSR range

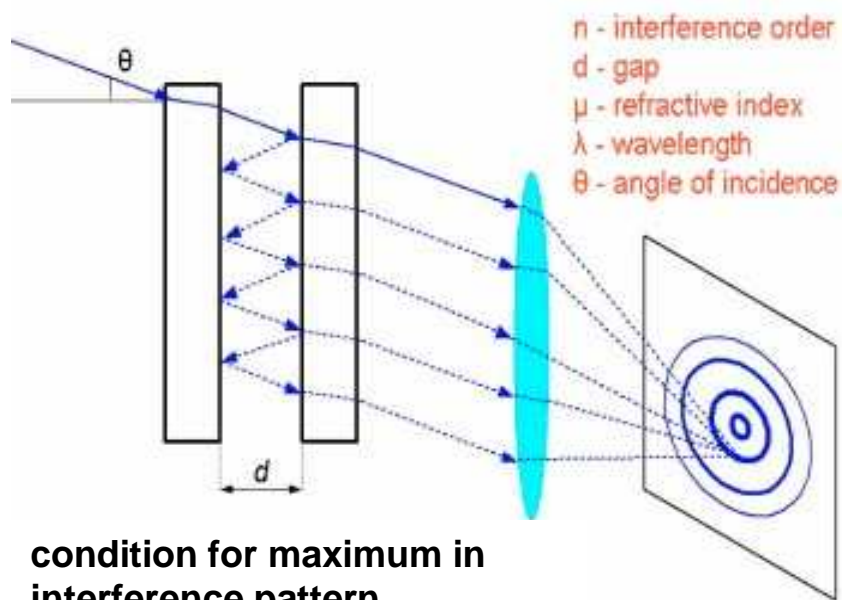
dewar test changed same amount of volts and got the expected $\sim 1/2$ FSR motion



Scaling observed PZT scan distance

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condition for maximum in interference pattern

$$n\lambda = 2d\mu\cos\theta$$

Fringe at specific FPA location
whenever gap changes by

$$\Delta d = \lambda / (2\mu \cos\theta) \sim \lambda / 2$$

$$[\lambda_{\text{laser}} = 9.473 \mu (1055.63 \text{ cm}^{-1})]$$

$$\Delta d = 4.7365 \text{ micron}$$

Change in PZT gap needed to change
fringe order at specific FPA pixel

~ 0.5 Δd observed in dewar data

~ 2.4 micron movement (15 V Δ PZT)

100 V PZT range ~ 6.67*2.4 micron

~ 16 micron full-range estimated

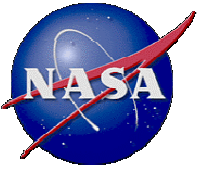
43 micron observed @ ambient

~ 21.5 micron expected in dewar

~ 75% achieved (from linear extrapolation)

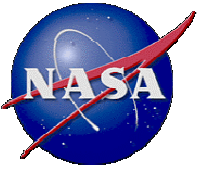
$\Delta V / \Delta \text{PZT}$ is known to be nonlinear

~ ballpark cryogenic PZT motion from
observed PZT-scan-induced spectral fringes



Spectral Fringe “Proof”

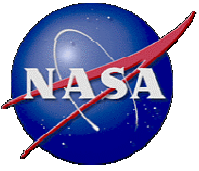
- Moving fringe pattern observed with Δ PZT while viewing monochromatic source
- Upon changing CO₂ laser lines, spatial-positioning of fringe pattern changed on FPA
- Etalon & PZT characteristics derived from HRE/dewar-induced fringes comparable to those derived in bench-level ambient testing
 - N_e
 - PZT scan response
- **Demonstrates existence of imaging FPI!**



H/W / setup mods since IIP “closure”

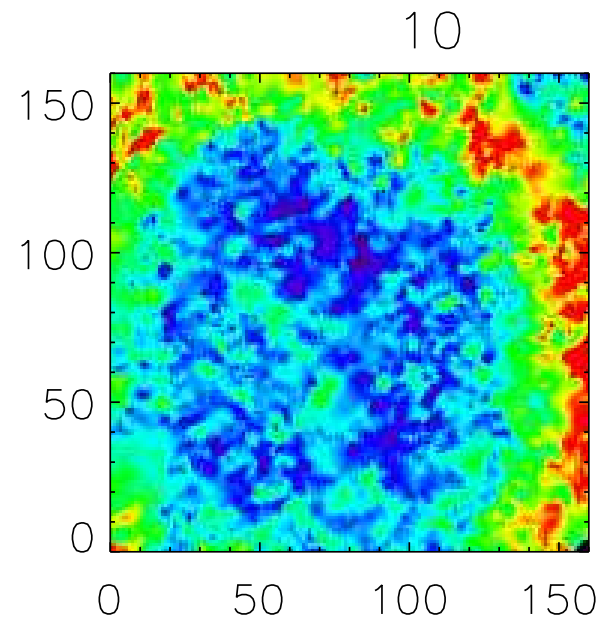
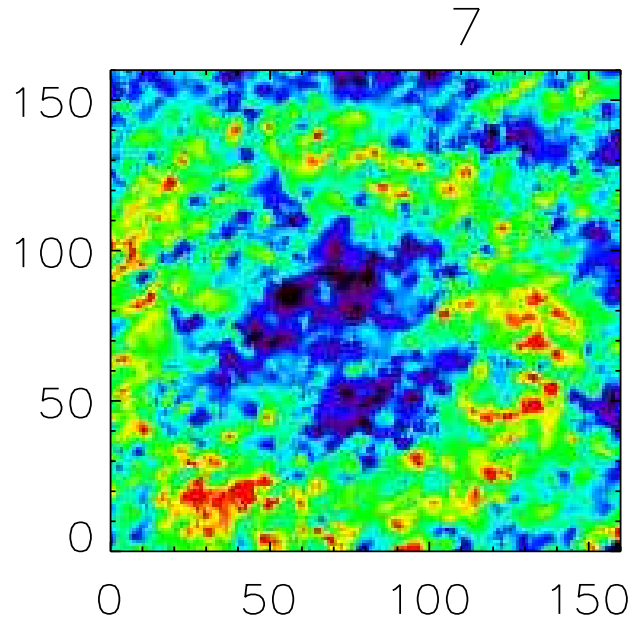
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- **PZTs worked in dewar on 15 March, but motors not operable (insufficient torque & lubricants not functional at cryogenic temps; no ability to align) and did not have any measure of capacitance (i.e. no proof of repeatability in dewar). Also, FPA was only partially illuminated.**
 - [Aside: PZT stacks designed to provide needed spectral scan displacement, but not extra for initial alignment; i.e., ~ 45 micron motion @ room temperature, and ~ 1/2 distance @ 77K in dewar]
- **Purchased non-cryogenic-rated motors with required torque and converted to enable cryogenic operation**
 - removed all bearing seals & lubricants and degreased all parts using ultrasonic cleaning. Qualified motors by submerging in liquid nitrogen bath. Cryogenic performance demonstrated within dewar
- **Cryogenic capacitance monitoring enabled by altering capacitor spacings to match dynamic range of PZT motion**
- **Full-FPA illumination achieved using integrating sphere or diverging lens in pre-optics**

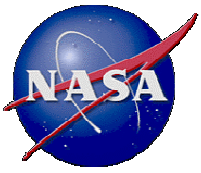


First full-FPA illumination of monochromatic source (22 May)

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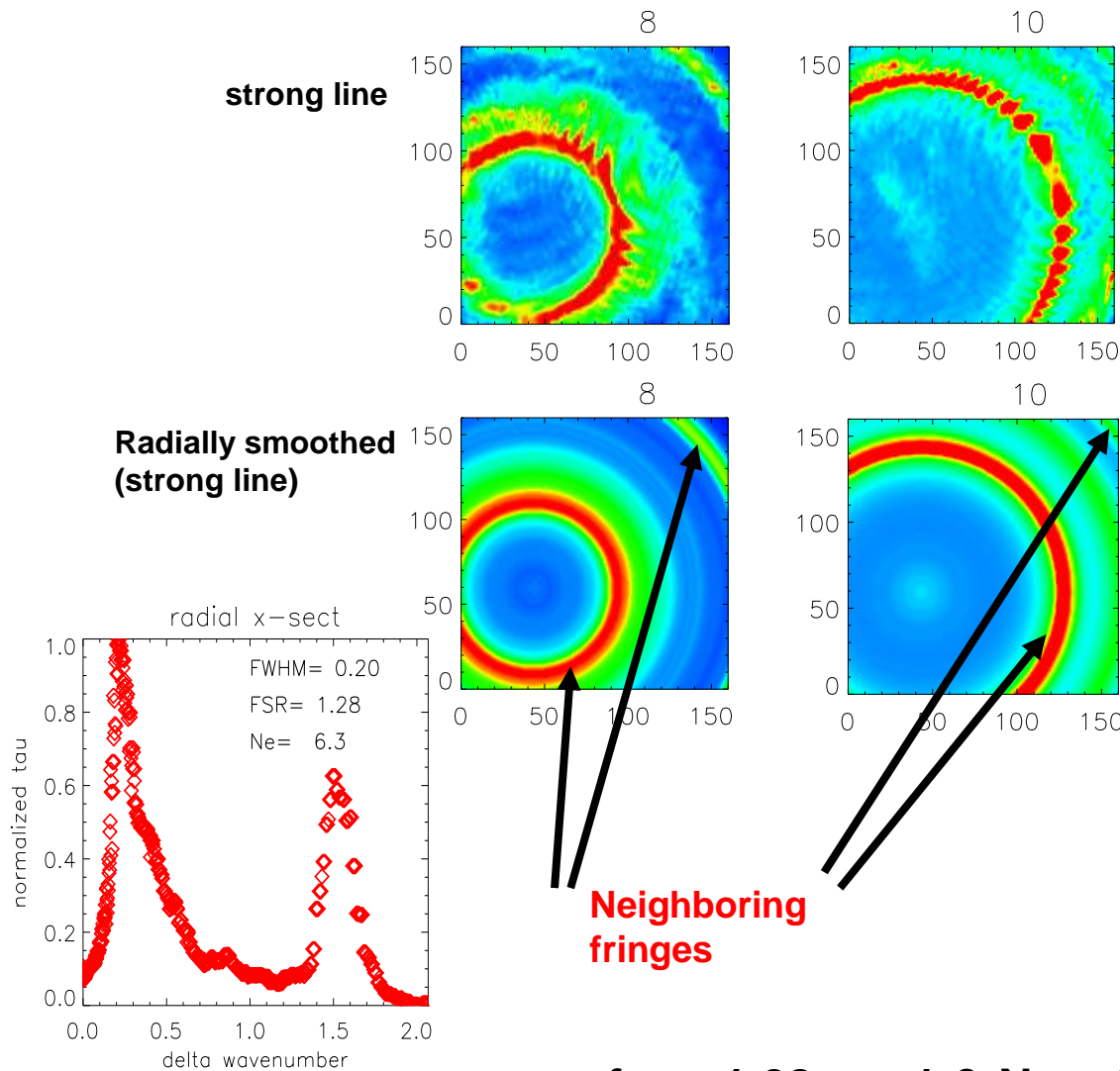


- used integrating sphere for “extended source”
- warm (77 K) operation resulted in weak target signal relative to other parasitic components, but did show complete spectral fringes in dewar!



Etalon properties from neighboring fringes: higher signal test (7 June)

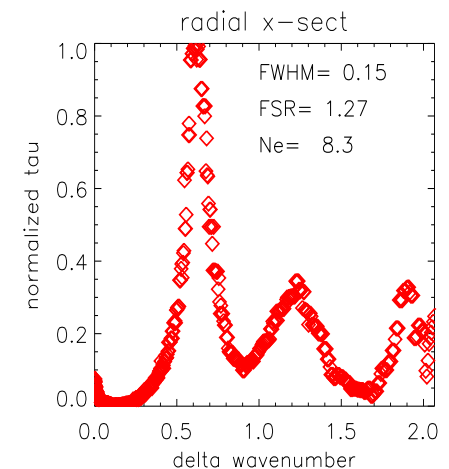
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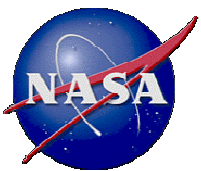
Radial x-section
for pos-8

$\text{fsr} \sim 1.28 \text{ cm}^{-1}$ & $\text{Ne} \sim 8.2$

- w/o integrating sphere; lens used to diverge beam and illuminate entire FPA
- Shows:
 - multiple superimposed fringe patterns (spectral & spatial)
 - optical mis-alignment

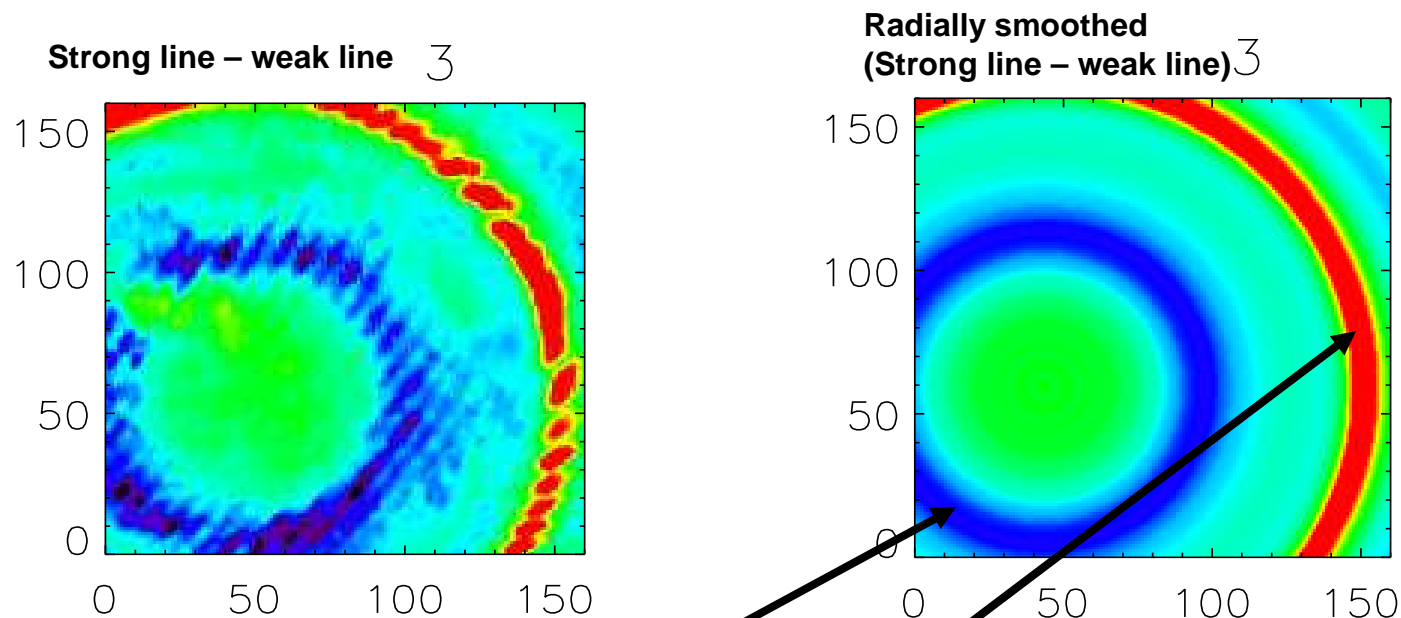


Radial x-section
for pos-10



Difference images of two laser lines observed at select *same* capacitance positions (7 June)

[Viewing 2 lines enables etalon spectral property determination from single image]



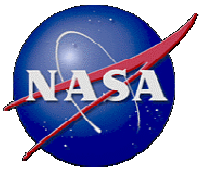
Weak line
position

Strong line
position

Yields 0.83 cm⁻¹ difference;
should be wavelength diff +/- n*fsr

9.473micron - 9.504 micron = 3.4432 cm⁻¹

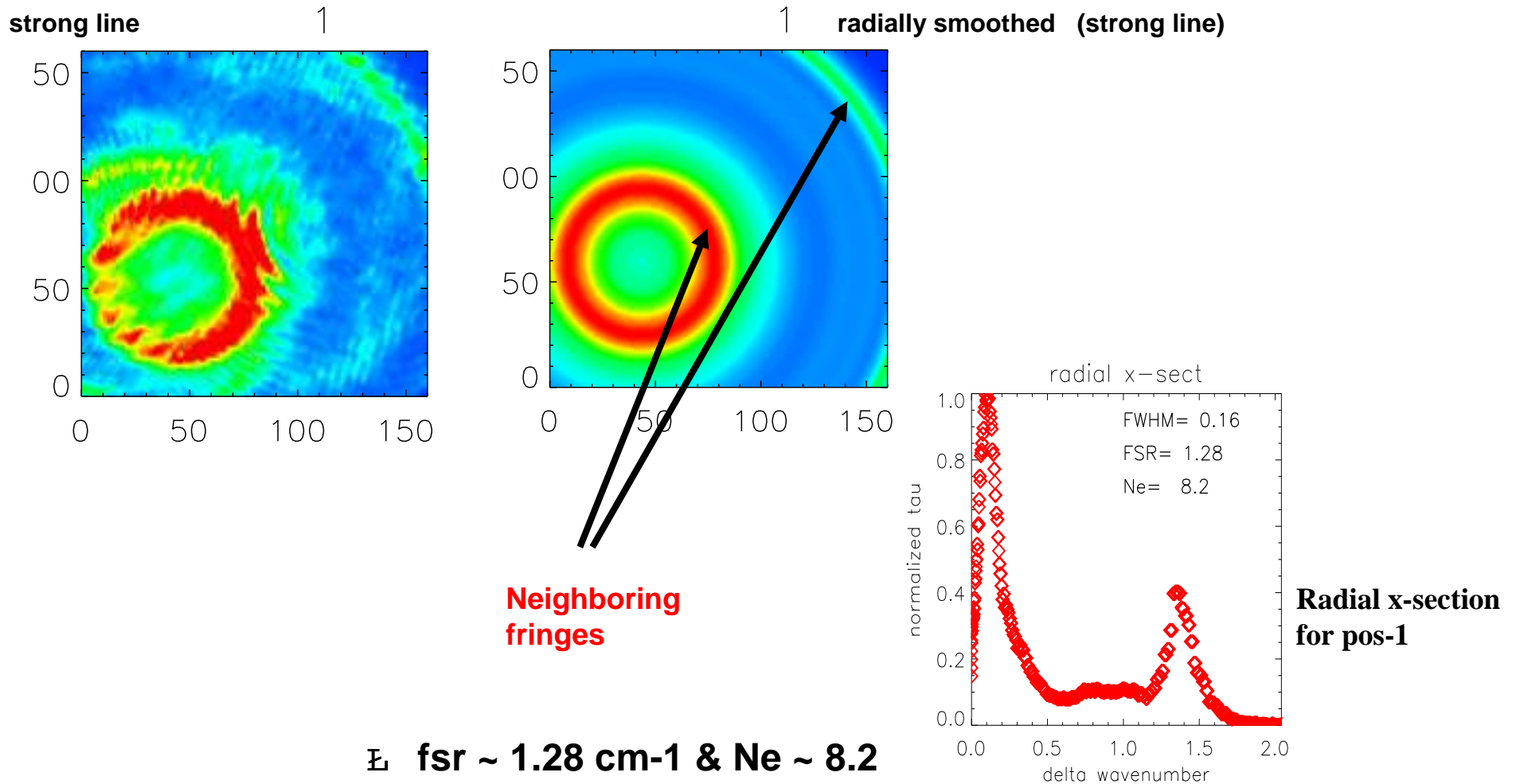
0.83 cm⁻¹ + n*1.28 = 3.39, n = 2 (~ 1.5% error)

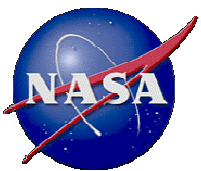


Spectral properties are repeatable (9 June)

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Similar characteristics as observed during 7 June testing



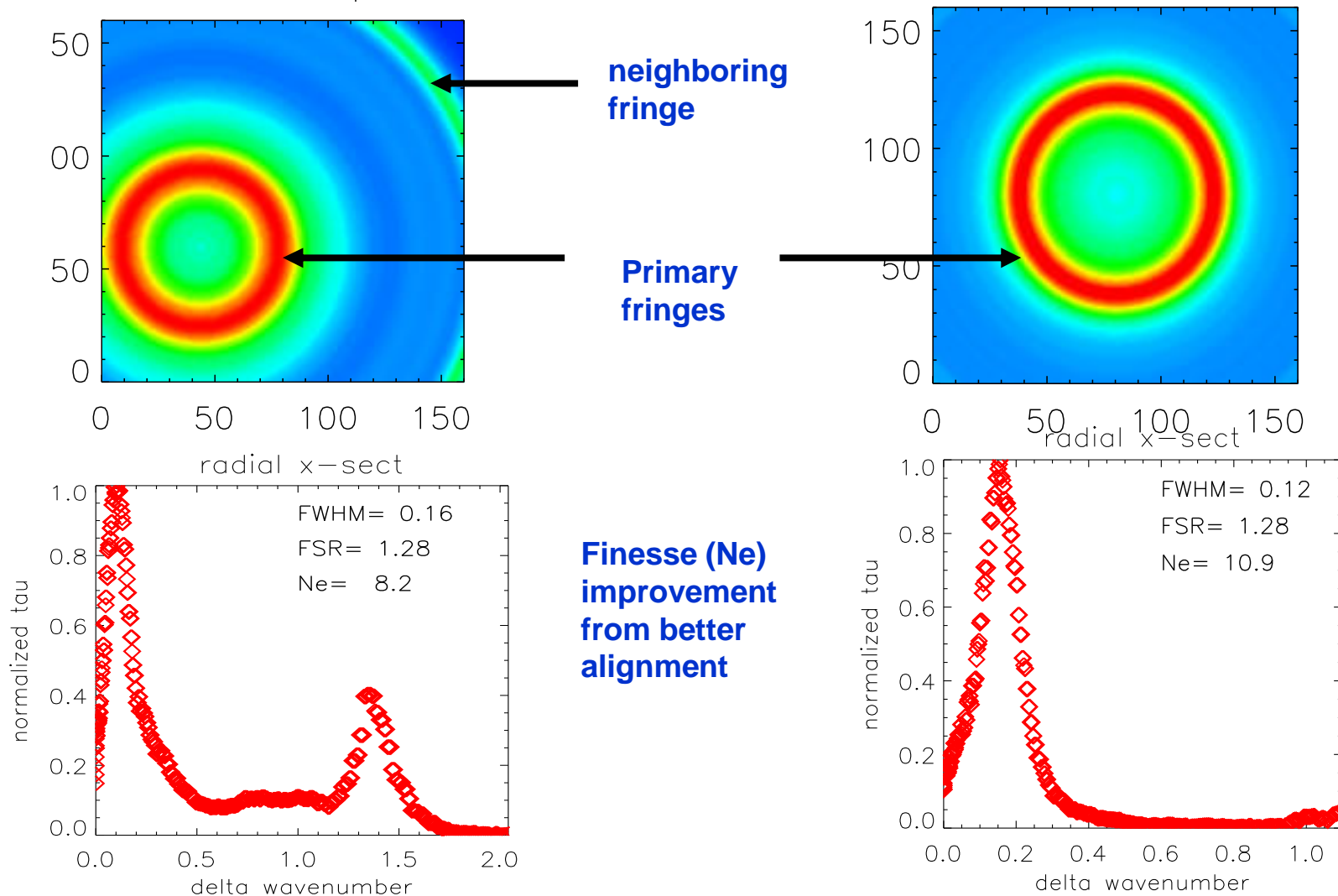


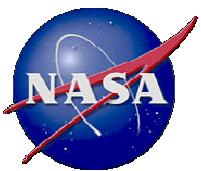
Fringe pattern characteristics before/after centering (9 June)

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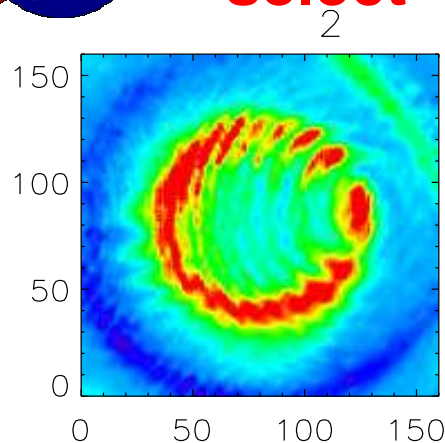
[Centering performed using alignment adjustment motors]

3

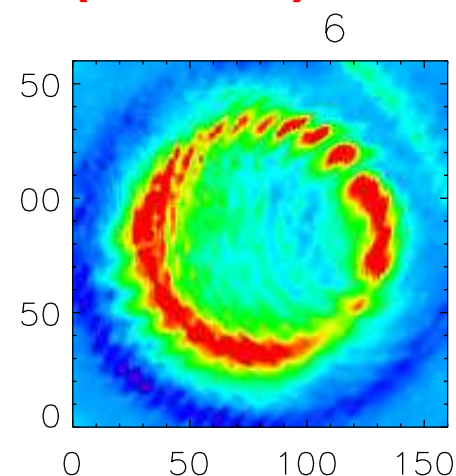




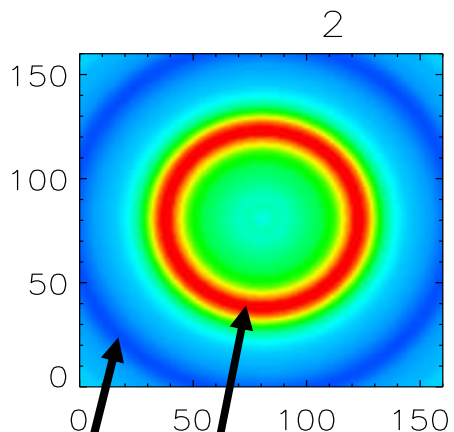
Difference images of two laser lines observed at select *same* capacitance positions (9 June): centered fringe pattern



Strong line – weak line



Radially smoothed (Strong line – weak line)

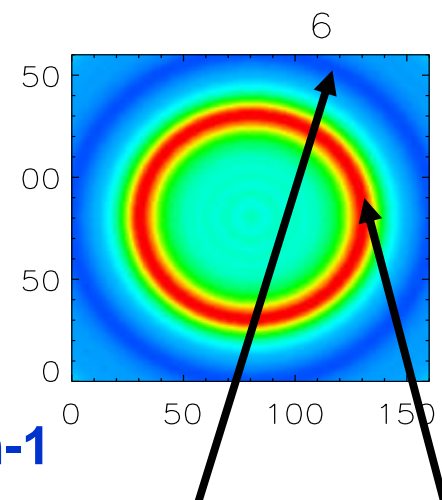


$$3.4432 = n \cdot \text{fsr} + \text{dv} \quad \text{FSR} = \frac{3.4432 \pm \text{dv}}{n}, n=1,2,3,\dots$$

Pos-2: $\text{fsr} = (3.4432 + 0.44)/3 = 1.294 \text{ cm}^{-1}$

Pos-6: $\text{fsr} = (3.4432 + 0.37)/3 = 1.271 \text{ cm}^{-1}$

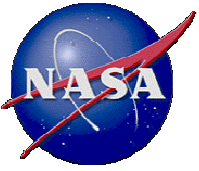
AVG = 1.283 cm^{-1} (0.23% > “truth”)



weak line
position

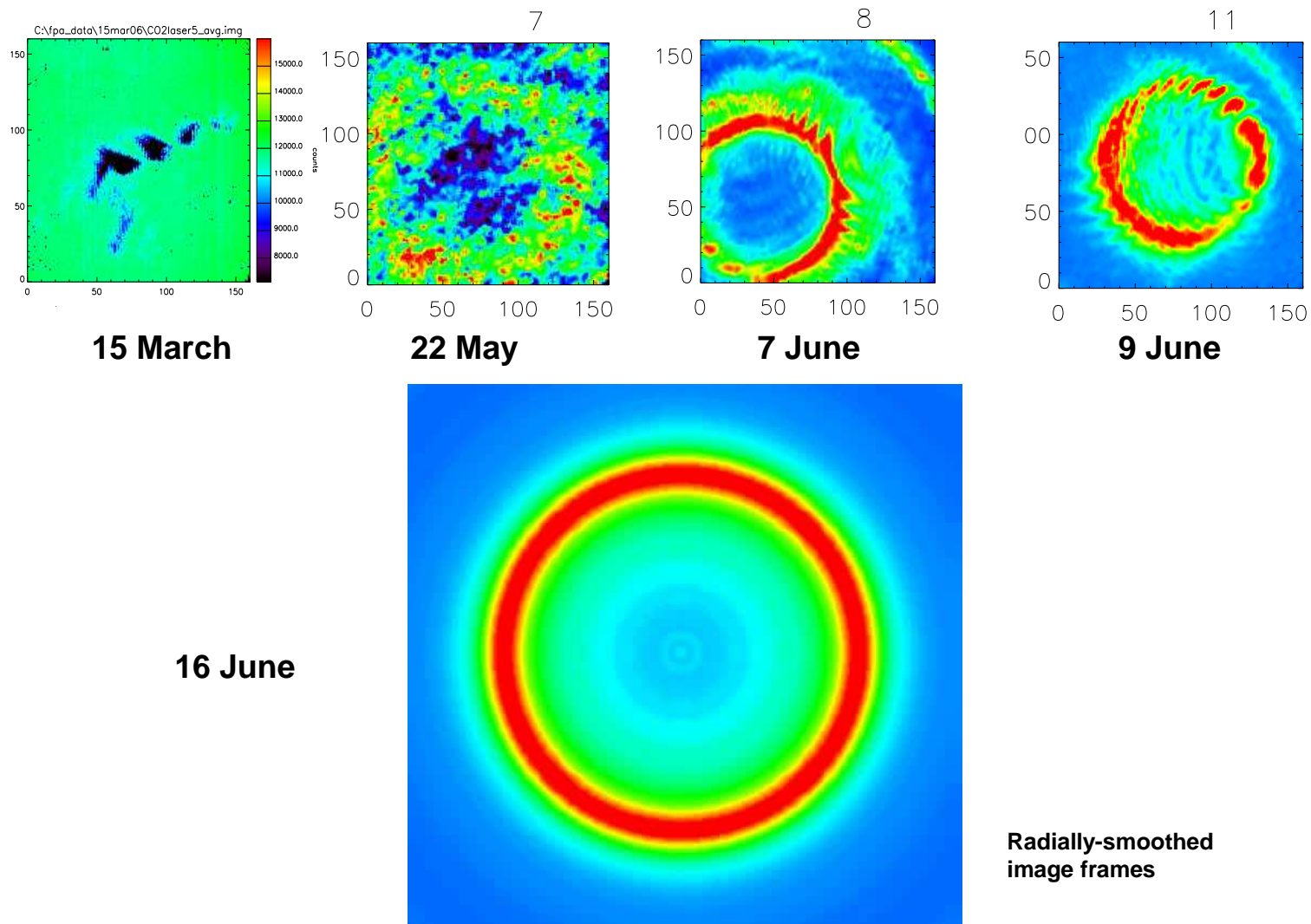
Strong line
position

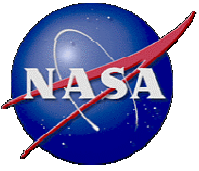
weak line
position



TTSS-FPI fringe pattern evolution

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Technology Demonstration Status

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- **Radiometric calibration**

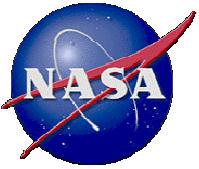
- Radiometric calibration methodology fidelity has been demonstrated in the cryogenic dewar environment by using cold, thermally-stable FPA measurements of known target temperatures to show radiometric calibration transforms measurements to expected scene temperatures with greatly reduced pixel-variance over uniform scenes. (Calibration-target & hallway tests)

- **Spatial imaging**

- Spatial imaging fidelity has been demonstrated in the cryogenic dewar environment by FPA-inferred spatial sizes matching known-target dimensions (sun-look & hallway tests)

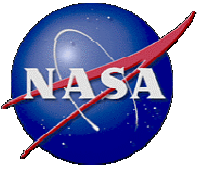
- **Spectral tuning**

- Spectral tuning fidelity has been demonstrated in the ambient lab and cryogenic dewar environments by being able to precisely repeat desired spectral characteristics via etalon gap control (sun-look, capacitance repeatability, PZT & motor scan tests)



Way Forward

- Technical advancement
 - autonomous tuning & control
 - Capacitance feedback system
 - Image quality & radiometric crosstalk
 - stray light reduction
 - AR-coated dewar window
 - Additional baffling/optical elements or tilting to minimize impact of undesired reflections-induced spatial/spectral parasitic energy
 - Implement double-etalon SRF
 - Insert LRE in etalon assembly
- Demonstrations
 - Lab testing/characterization (including atm/solar views)
 - Consider field deployment(s), aircraft implementation
- Program infusion
 - ESSP (SMD)
 - External applications (DOD, IC, etc.)



Conclusion

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- § Tropospheric ozone is a **HIGH-PRIORITY measurement** in the NASA SMD Strategic Enterprise and Science Research Plans
- § TTSS-FPI concept enables **new multispectral imaging measurement capability** for space-based observation of tropospheric ozone
- § Exploits **spatial and temporal benefits** of GEO-imaging (e.g. monitoring of regional pollution episodes)
- § Instrument concept and **technologies** also have **broad-based applicability** to measurement of other geophysical parameters (passive & active)
- § Hybrid instrument implementations (e.g. FPI + FTS) can **greatly simplify sensor designs** where high spectral resolution is needed in only select spectral regions
- § Instrument system (TTSS-FPI) development within NASA's IIP has **demonstrated an advanced atmospheric remote sensor concept & technologies** intended for geostationary-based measurement of tropospheric O₃
 - § Imaging cryogenic FPI has been demonstrated
 - Very encouraging Radiometric, spatial, and spectral performance has been characterized